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RESEARCH MEMORANDUM

for the

Bureau of Ordnance, Department of the Navy

SUMMARY OF INVESTIGATIONS OF MARK 25 AERIAL-TORPEDO TURBINE

By Harold J. Schum, Warren J. Whitney
and Howard A. Buckner, Jr.

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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SUMMARY

The power plant from a Mark 25 aerial torpedo was investigated both as a two-stage turbine and as a single-stage modified turbine to determine the effect on over-all performance of nozzle size and shape, first-stage rotor-blade configuration, and axial nozzle-rotor running clearance. Performance was evaluated in terms of brake, rotor, and blade efficiencies. All the performance data were obtained for inlet-total- to outlet-static-pressure ratios of 8, 15 (design), and 20 with inlet conditions maintained constant at 95 pounds per square inch gage and 1000° F for rotor speeds from approximately 6000 to 18,000 rpm.

The highest brake efficiencies for both the two-stage turbine and the single-stage modification were obtained with the nozzle having the largest total passage area, designated nozzle H. A maximum brake efficiency of 0.49 was obtained with the standard two-stage turbine at a pressure ratio of 15. The best single-stage performance resulted when nozzle H was operated in combination with a rotor having a blade height of 0.45 inch; the resulting maximum obtained brake efficiency at design speed and pressure ratio was 0.50. Comparison of the power output of the two-stage turbine and the single-stage unit indicated that the first stage developed most of the shaft power. A change in axial operating clearance between the nozzle and the rotor from 0.030 to 0.150 inch had little effect on turbine performance when the unit was operated with a non-divergent nozzle. When a converging-diverging nozzle was used, however, a decrease in brake efficiency of 0.06 at the maximum speed was noted when the clearance was increased from 0.030 to 0.095 inch. Although the blade efficiency of the single-stage turbine varied

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somewhat with different nozzles, no specific trend of efficiency with nozzle size or shape within the range investigated could be established. Increasing the blade height from 0.35 to 0.45 inch resulted in an increase of blade efficiency from 0.47 to 0.54 at design conditions with nozzle H. The effect on the performance of the single-stage turbine of changing the blade-inlet angle from 17° to 20° was negligible.

Consideration of the losses affecting the turbine performance indicated that any further improvement must originate from decreasing the following losses: (a) leaving losses that could be partly recovered by either a more effective second stage or by a suitably designed stator row and diffuser; and (b) losses resulting from large turning of supersonic flow, which might be decreased by an improved blade-passage design.

INTRODUCTION

Torpedoes operating on a combustion cycle require a high-pressure-ratio low-speed gas turbine to drive the propellers of the unit. Some types of rocket require similar turbines to power the fuel or propellant pumps. Both applications involve the extraction of maximum power with minimum size and weight of power plant, combustion constituents, and gearing. Because of the need for information on turbines of this type, at the request of the Bureau of Ordnance, Department of the Navy, an extensive investigation was made at the NACA Lewis laboratory on the two-stage counterrotating impulse turbine from the Mark 25 aerial torpedo.

Because of the aforementioned design requirements, this particlar turbine had an 11-inch blade-tip diameter, a 90° arc of admission, small nozzle- and rotor-passage areas, supersonic-design velocities relative to the first rotor, and counterrotation of the second rotor to minimize gyroscopic effects. In a turbine of this size and type, it is at present virtually impossible to predict the performance on the basis of a sound design method. The investigation consisted principally of the experimental determination of the performance both of the standard turbine and of the turbine with modified components inasmuch as detailed flow measurements within the turbine could not be obtained with available methods. Among the variables investigated were nozzle-passage size and shape, first-stage rotor-blade height and inlet angle, and shrouding of the first-stage rotor. Also investigated were the division of work between the two stages, the effect of axial nozzle-rotor clearance, and the magnitudes of such losses as disk windage, rotor-blade pumping losses, and mechanical losses.

The results of these studies are given in references 1 to 8 and are summarized herein with a discussion of the source of the losses affecting turbine performance.

APPARATUS AND PROCEDURE

Turbine. - The Mark 25 aerial-torpedo power plant is a two-stage counterrotating impulse turbine, designed to operate at a pressure ratio of 15 and a turbine speed of 18,000 rpm. The two turbine rotors are geared to operate at the same rotative speeds but in opposite directions. The shroud-band diameters of the forward and rear turbine rotors are 11.00 and 11.32 inches, respectively; the corresponding blade lengths are 0.40 and 0.55 inch. Pitch diameter of both rotors was 10.48 inches. An axial clearance of 0.150 inch between the two rotors was maintained.

The turbine operates with nozzles that effect a 90° arc of gas admission. Design specifications require the gas to expand through the nozzles and to enter the forward turbine blades at supersonic relative velocities. Because most of the gas-velocity energy is absorbed by the forward turbine rotor, the flow leaving the first stage and entering the second stage is subsonic for idealized flow. The second-stage turbine rotor is designed for a small amount of reaction. This rotor is included in the design primarily for eliminating gyroscopic action.

In order to obtain the single-stage data, the turbine was modified and investigated as a single-stage unit. A description of the standard turbine and the modifications necessary to convert the two-stage unit into a single-stage turbine are given in references 1 and 2, respectively.

Nozzles. - Eight nozzles were investigated in all. Alphabetical notation of the nozzles was arbitrarily selected to distinguish the various nozzle designs as supplied by the manufacturer. All nozzles are described in references 1, 3, and 5. The different design variables of these nozzles are summarized in the following table:

Nozzle	Number of ports	Port-inlet configuration	Port cross-sectional shape	Total measured throat area (sq in.)	Ratio of outlet area to throat area
A	9	Rounded	Rectangular	0.183	1.47
E	9	Rounded	Circular	.193	1.00
F	3	Rounded	Circular	.064	1.00
G	9	Rounded	Circular	.193	1.00
H	9	Sharp-edged	Rectangular	.226	1.12
I	9	Sharp-edged	Rectangular	.217	1.20
J	9	Sharp-edged	Rectangular	.191	1.11
K	8	Sharp-edged	Circular	.153	1.16

All nozzles effect a 90° arc of gas admission to the turbine rotor with the exception of nozzle F, which is designed with a 30° arc of admission but is otherwise similar to nozzle E. Nozzle G is also similar to nozzle E but was designed with an axially projecting shroud in order to provide a more favorable flow profile and to prevent combustion gases from spilling over or above the first-stage rotor. Photographs of two representative nozzles are shown in figure 1.

Blades. - The standard first-stage rotor of the Mark 25 turbine has shrouded blades 0.40 inch in height with an air-inlet angle of 17° and an outlet angle of 16°. First-stage rotor-blade modifications investigated are described in detail in reference 4 and are summarized in the following table:

Blade height (in.)	Blade-inlet angle (deg)	Blade outer shroud
0.40	20	Yes
.35	17	Yes
.45	17	Yes
.35	17	No

Setup and instrumentation. - The setup used in the experimental investigation of the two-stage Mark 25 aerial-torpedo turbine is shown in figure 2. A 300-horsepower electric dynamometer was used to absorb turbine power and to drive the unit during motoring runs. Combustion gases were supplied by a burner using unleaded gasoline. The air flow was supplied by the laboratory service-air supply and was metered by an A.S.M.E. standard flat-plate orifice. After the air had passed through the turbine, it was discharged into the laboratory exhaust system. A schematic drawing of the nozzle and the two-stage turbine-rotor assembly is presented in figure 3. During the single-stage investigation, the rear turbine rotor was replaced by a disk and the drive gear was removed. Sheet-metal straightening vanes were mounted on the disk to direct the discharge gas into the exhaust. All of the nozzle-rotor axial clearances were maintained at 0.030 inch except in the experiments to determine the effect of varying this clearance and in the single-stage investigation with nozzle K when the unit was operated with 0.040-inch clearance. In this range of axial running clearances, performance would be unaffected by a 0.010-inch change in clearance (reference 3).

Turbine speed, dynamometer torque, pressures, and temperatures were measured in the same manner as described in reference 1.

Procedure. - The experimental research program for the Mark 25 aerial-torpedo power plant consisted of the determination of the effects of (1) nozzle design, (2) axial nozzle-rotor clearance, and (3) first-stage blade design on over-all performance. Results of the investigations with the various nozzle and rotor configurations are presented in references 1 to 8. Performance was presented in terms of brake, rotor, and blade efficiencies as functions of the blade-jet speed ratios. The parameters and the methods used in calculating the efficiencies are described in references 1 and 3, using the air tables of reference 9. Efficiencies were based on the inlet-total- to outlet-static-pressure ratio. Turbine-inlet conditions were maintained constant at a pressure of 95 pounds per square inch gage and a temperature of 1000° F. Runs were made at pressure ratios of 8, 15 (design), and 20 for the various nozzle-rotor combinations, with the exception of nozzle H, which was necessarily run at a pressure ratio of 19. The turbine speed was varied from approximately 6000 rpm to the design speed of 18,000 rpm for each pressure ratio and nozzle-rotor configuration.

Mechanical and windage losses were evaluated for both the single- and the two-stage turbine by motoring each unit over a range of speeds and varying the air density in the turbine casing at each speed. The power required to motor the unit was measured; this power was equal to the combined mechanical and windage losses. The mechanical loss at any speed was determined by extrapolating the necessary power input to an air density of zero. A detailed description of the method and the quantitative values of these losses are presented in references 1 and 2.

RESULTS AND DISCUSSION

The general results of the investigation and a consideration of the effects on performance of the losses incurred in a turbine of this type are discussed in the following paragraphs.

Experimental Results

Two-stage turbine performance. - The two-stage Mark 25 aerial-torpedo turbine with standard rotor blades was operated in combination with six nozzles, A, E, F, G, H, and I. The highest efficiencies were observed when the unit was operated with nozzle H. The performance of this combination is summarized in figure 4 in terms of brake, rotor, and blade efficiencies as functions of the blade-jet speed ratio for the three pressure ratios investigated. A brake efficiency of 0.49 was obtained with nozzle H at a blade-jet speed ratio of approximately 0.27 for a pressure ratio of 15 (fig. 4(b)). At corresponding conditions, the rotor efficiency (which credits the turbine with the mechanical losses) was approximately 0.54. If the turbine is also credited with the work necessary to overcome the windage losses, a blade efficiency of approximately 0.60 was obtained. Nozzle H also provided the maximum obtained blade efficiency of 0.64 at a pressure ratio of 8 and a blade-jet speed ratio of 0.295 (fig. 4(a)). The difference in the general trends of the brake- and blade-efficiency curves at any pressure ratio can be ascribed to the approximate cubic increase of windage losses with speed.

Effect of axial nozzle-rotor clearance. - The standard two-stage turbine was operated over a range of axial nozzle-rotor clearances from 0.030 to 0.150 inch using several nozzles, and the performance was determined. Results are presented in reference 3. The blade efficiency as a function of clearance at various blade-jet speed ratios for two types of nozzle at the design pressure ratio of 15 is presented in figure 5. Blade efficiency was considered a better criterion for comparing performance than brake or rotor efficiency because the effects of mechanical friction and windage are eliminated. Little effect on performance was noted when the turbine was operated in conjuction with nozzle E, a nondivergent type; the efficiencies remained relatively constant over the range of clearances (fig. 5(a)).

When nozzle H, a sharp-edged inlet nozzle with convergent-divergent passages, was investigated, more sensitivity of efficiency with axial nozzle-rotor clearance was discernible (fig. 5(b)) than for the nondivergent nozzle. A decrease in efficiency 0.06 was noted as the clearance was increased from 0.035 to 0.095 inch for a constant blade-jet speed ratio of 0.24. Investigation of the turbine with greater clearance was not considered imperative because the efficiency decreased with increasing clearance. For the Mark 25 torpedo turbine, small axial clearances were therefore desirable in order to obtain the best turbine performance with nozzles in which the gas expansion occurred within the passages proper.

Division of work between stages. - A comparison of brake, rotor, and blade efficiencies of the single and two-stage turbines using nozzle H and the standard first-stage rotor blades at the design pressure ratio of 15 is given in figure 6. At the greatest blade-jet speed ratio obtained (0.27), the brake efficiency of the two-stage turbine was approximately 0.02 higher than that obtained with the single-stage turbine. Because of the much higher disk and blade windage losses encountered in the two-stage turbine, the maximum brake efficiency was reached at a lower blade-jet speed ratio than in the single-stage turbine. The efficiency of the single-stage turbine increased with increasing speed; the peak efficiency was never reached because of the design-speed limitation. The importance of windage losses in a small partial-admission-type turbine is well illustrated by the large difference of 0.10 in blade efficiency and the small difference of 0.02 in brake efficiency between the two turbines at a blade-jet speed ratio of 0.27. Although the maximum brake efficiency of the two-stage turbine was 0.06 greater than the highest measured efficiency of the single stage, the second stage of the turbine actually contributed very little to the total power output. At low pressure ratios, the windage and mechanical losses exceeded the blade power of the second stage, resulting in an over-all power loss when the second stage was added to the turbine. (See reference 2.) Because the second stage contributed very little to the total power output, the remainder of the experimental work was concerned principally with the modified single-stage turbine.

Effect of nozzle configuration on single-stage turbine performance. - The effect of nozzle configuration on blade efficiency is shown in figure 7 for the standard first-stage rotor and the three pressure ratios investigated. At a pressure ratio of 20, a difference of 0.05 occurs in maximum efficiency. This difference is slightly smaller at the pressure ratios lower than 20. No specific trend of efficiency with either nozzle size or shape could be established for the six nozzles investigated. Results obtained with the same nozzles when investigated with the two other first-stage rotors (reference 8) are comparable in this respect. The preceding observation is not intended to imply that nozzle size and shape do not affect the over-all turbine performance, but rather that in this investigation these characteristics were not varied independently or over a wide range and the effect of changing either size or shape cannot be isolated. Efficiency for all nozzle-rotor combinations decreased with increasing pressure ratio.

Effect of first-stage rotor-blade configuration on single-stage turbine performance. - The effect of rotor-blade height, blade-inlet angle, and blade shrouds on turbine-blade efficiency is shown in figure 8 for nozzle H. This particular nozzle was selected because, when operated with the rotor having 0.45-inch blades, it provided the highest efficiencies. The maximum blade efficiency at design speed and pressure ratio was 0.54. The maximum brake efficiency for this combination was 0.50 (reference 4), obtained at corresponding operating conditions. The detrimental effect on performance caused by removing the blade shrouds or by replacing them with a close-fitting stationary shroud cap can be ascertained by comparing the efficiencies obtained with the three 0.35-inch-blade configurations in figure 8. At a pressure ratio of 15, a decrease of 0.07 in efficiency resulted when the shrouds were removed from the 0.35-inch blades.

The flow passages of the 0.35-inch (shrouded), the 0.40-inch (standard), and the 0.45-inch rotor blades are of the same design; the only variable is the blade height. A comparison of the performance of nozzle H with these three blade configurations indicates that blade height has an appreciable effect on over-all efficiency; the efficiency increased from 0.47 to 0.54 with an increase in blade height from 0.35 to 0.45 inch at design speed and pressure ratio. Whether or not the efficiency could be increased by using longer rotor blades in combination with nozzle H is problematical. An effect of blade height on efficiency is also illustrated in reference 8 where nozzle K was found to give better performance with the standard 0.40-inch, 17°-inlet-angle-blade rotor than with the 0.45-inch-blade rotor. Thus for any nozzle there apparently is an optimum blade height. Attributing this effect directly to the ratio of rotor-passage area to nozzle-passage area is difficult, however, because the nozzles had different design characteristics. The nozzle passages differed in cross-sectional area and shape, area divergence ratio, and velocity coefficient; the difference in these characteristics individually affect the over-all turbine performance. The effect on performance of increasing the rotor-blade inlet angle for a 0.40-inch blade from the standard 17° to 20° is shown in figure 8. The change in blade efficiency is practically negligible. The relation is also generally true when the data of reference 2 are compared with the tabulated efficiencies in reference 4.

Two-stage turbine with most efficient nozzle-rotor combination. - From the nozzle and blade-shape experimentation, the most efficient single-stage combination (nozzle H and 0.45-in.-blade rotor) was ascertained and this configuration was operated with the standard second-stage rotor to determine the performance of the resulting two-stage unit. The resulting efficiencies were lower than the efficiencies obtained for the standard Mark 25 first-stage rotor (reference 4). This decrease was presumed to be caused by unfavorable inlet-gas velocities and inlet angles to the second stage due to the greater blade heights of the first-stage rotor, which caused the second stage to be of reduced effectiveness.

General Discussion of Losses

The original Mark 25 aerial-torpedo turbine was designed as a two-stage counterrotating turbine. This design feature was necessary to eliminate gyroscopic action that would be detrimental to torpedo control. Because there was no stator row between the rotors and both rotors had essentially impulse blades, the kinetic energy leaving the first rotor was quite high. The second stage converted only a part of this kinetic energy into shaft power. Because of the complexity of interpreting the results of changing the nozzle-rotor combinations, a large part of the work was done on the single-stage unit. In accordance with this procedure, the following discussion of losses is concerned, in general, with the single-stage turbine.

From the various single-stage nozzle-rotor configurations investigated, a spread in the maximum brake efficiency of 0.18 was obtained at design pressure ratio (reference 4). The best single-stage combination, which consisted of nozzle H and the rotor with 0.45-inch blades, yielded a brake efficiency of 0.50 (reference 4) and a corresponding blade efficiency of 0.54 (fig. 8(b)). Although the results represent a sizeable improvement over other combinations investigated, the highest efficiency obtained was quite low. This low efficiency is due partly to certain inherent losses that exist in turbines of this type. These losses result from the general design requirements of maximum power extraction per unit mass flow for an extremely small given mass flow, which, when combined with the speed limitation dictated by gearing, size, weight, and strength requirements, results in a low power output per unit diameter. Consequently, the losses represent a larger-than-normal portion of the total power. In addition to disk windage, mechanical, and tip-leakage losses, partial-admission losses consisting of rotor-blade pumping and filling and emptying (scavenging) losses occur for a nozzle arc of 90° (reference 10). When these losses are added to inherent viscous and momentum losses resulting from high velocities in extremely small flow channels, the turbine performance is seriously limited.

The total magnitude of disk windage, mechanical, and rotor-blade pumping or windage losses is reflected in the difference between brake and blade efficiencies. For the best configuration at design pressure ratio and blade-jet speed ratio, this difference amounted to 4 percent of the isentropic power. Of this total, disk-windage, mechanical, and rotor-blade-windage losses constituted 0.4, 2.5, and 0.9 percent, respectively. The difference between the blade efficiency of 0.54 and 1 represents the part of the isentropic power consumed by leaving, aerodynamic, tip-leakage, and partial-admission-scavenging losses. Because this turbine is an impulse type with shrouded blading, the leakage losses would be relatively small. The remaining 46 percent of the available power can therefore be attributed primarily to leaving, aerodynamic, and partial-admission-scavenging losses.

Leaving losses. - Leaving loss is defined herein as the kinetic energy of the gas leaving the turbine. For the single-stage configuration of the Mark 25 turbine, an approximate calculation indicated that this loss may be as large as 24 percent of the isentropic power at design conditions. This estimate is based on the difference between efficiencies calculated on total-to-total and total-to-static pressure-ratio basis for ideal flow when a fully expanding nozzle and a pure impulse turbine are assumed. Although the leaving loss would probably be somewhat less than this value, the single-stage efficiency is limited to approximately 0.76 by this loss.

As previously mentioned, the large kinetic energy leaving the first stage was a result of the design requirement of counterrotation without a stator row between the rotors and the requirement of low speeds.

For the nozzle and first-stage-rotor combination discussed, the blade efficiency at design conditions for the two-stage turbine was about 0.04 greater than for the single-stage unit, indicating that only a small part of this kinetic energy was recovered by the second-stage blades (reference 4). Failure of the second-stage blade to recover more of the kinetic energy leaving the first stage may be attributed chiefly to the mismatching of the second-stage blade design to the outlet flow conditions from the first-stage blading. When the two-stage turbine was operated with the standard first-stage blades, thereby obtaining better matching of the two stages, the difference in blade efficiency amounted to 0.10 (fig. 6), indicating a somewhat larger recovery for the second stage. This increase in blade efficiency, however, represents an increase in brake efficiency of only 0.02 because of the large windage and mechanical losses of the second stage. A greater knowledge of the flow conditions leaving the first stage would certainly permit the design of a more effective second stage that would give a significant increase in brake efficiency, as well as blade performance. Another possible means of recovering this energy in the single-stage turbine would be the use of a suitably designed stator row and a diffusing section downstream of the rotor.

Aerodynamic losses. - Because the blade efficiency of the best nozzle-rotor configuration was 0.54 at design conditions and because the magnitude of the leaving losses reduce the efficiency from the order of 1 to 0.76, the remaining losses were also quite severe. Part of these losses were aerodynamic losses resulting from the large amount of turning of the gas at supersonic velocities. The first-stage rotor blades of the turbine were designed to turn the flow through 147° at an initial free-stream Mach number of approximately 1.6. At a given rotor-blade cross section, the flow area from rotor inlet to outlet was about constant and the blades had blunt leading edges. The convex and concave sides of the blades had constant curvature throughout almost the entire passage. The rotor-blade height was made nearly twice the height of the nozzle passages on the premise that the supersonic jet would automatically seek the proper flow area by resorting to radial divergence. Such radial motion, of course, would greatly influence the flow angle of the gas relative to the rotor. It is not certain that such conditions would permit maintenance of supersonic velocity near the blade-passage inlet. If subsonic velocities prevail in the blade passage, sizeable losses would occur as a result of the reduction of the total pressure and energy through the shock formation at the inlet.

If the flow entering the rotor passage is supersonic, some total-pressure and energy losses would occur because the blunt leading edges of the rotor blades would cause a detached bow wave. An oblique shock must exist near the blade inlet as a result of the wedge angle and subsequent turning. In order to avoid separation as a result of these shocks, careful consideration must be given to the design of the turning surfaces and the interaction of the expansion and shock waves. A preliminary examination of the wave formation in the blade passage by the method of characteristics has indicated that losses of this nature would result from the concentration of shock waves originating from the pressure surface of the blade and impinging on the convex surface of the adjacent blade where separation would amost certainly appear. Because the turbine-blade surfaces were of constant radii throughout most of the blade-passage length, the probability of efficient supersonic turning for any inlet condition is exceedingly small. Also, further losses would result from instability of the jet boundaries due to conflicting pressure and momentum forces and from viscous activity of the jet boundaries and the adjacent relatively stagnant fluid.

In either of the preceding cases, it is evident that significant improvements in turbine performance could be expected from careful design of the rotor blades considering wave formations and controlled annulus-area divergence.

Partial-admission scavenging losses. - The remaining losses result from filling and emptying of the rotor-blade passages as they pass into and out of the active arc of admission. For the turbine reported on in reference 11, as much as 25 percent of the isentropic available power was consumed by this loss and the diffusion loss resulting from nozzle leakage into the inactive space between the nozzle and the rotor for an arc of admission of 120°. This loss increased as the arc of admission was decreased. Although the diffusion loss would be less severe in an impulse turbine, the scavenging loss would still be sizeable because of the small arc of admission. Resorting to a greater arc of admission, however, would necessitate proportionately decreased blade height to conform to the mass-flow requirement. Inasmuch as the blade heights are already comparatively small, the losses associated with small blade heights would probably increase faster than the partial-admission losses decrease and this method of reducing the partial-admission losses would probably result in a lower over-all efficiency. These apparently large partial-admission losses are therefore considered inherent.

Probable sources of further improvement. - From the foregoing discussion, certain inherent losses apparently seriously limit the performance of turbines of this type. Among these losses are disk-windage, mechanical, tip-leakage, rotor-blade filling and emptying, and viscous and momentum losses resulting from high velocities in small passages. Consequently, further improvement in turbine performance would be expected to originate only from decreasing the remaining following losses: (a) leaving losses that could be partly recovered by either a more effective second stage or by a suitably designed stator row and diffuser; and (b) losses resulting from large turning of supersonic flow, which might be decreased by an improved blade-passage design.

SUMMARY OF RESULTS

An investigation of the turbine from a Mark 25 aerial-torpedo power plant yielded the following results:

1. The highest efficiencies for both the two-stage and the modified single-stage turbines were obtained when operated with the nozzle having the largest total passage area, designated nozzle H. At design speed and pressure ratio, the maximum brake efficiency of 0.49 was obtained with the standard two-stage turbine; the corresponding maximum brake efficiency for the single-stage turbine was 0.50 obtained with a rotor having 0.45-inch blades.

2. Varying the axial nozzle-rotor running clearance over a range from 0.030 to 0.150 inch had little effect on turbine efficiency when a nondivergent nozzle (E) was used. A converging-diverging nozzle (H) was sensitive to the effects of axial nozzle-rotor running clearance; a decrease in brake efficiency of 0.06 occurred when the clearance was increased from 0.030 to 0.095 inch at a constant blade-jet speed ratio of 0.24.

3. The first-stage turbine developed most of the power and the principal function of the second-stage rotor was to provide a counter gyroscopic effect. Moreover, at certain speeds the windage and mechanical losses of the second-stage rotor were greater than the power developed by this rotor and the net effect was to lower brake efficiency.

4. Although changes in efficiencies with various nozzle configurations were noted, no specific trend of single-stage blade efficiency with nozzle size or shape could be established from the data with the nozzles investigated.

5. A trend of blade efficiency with rotor-blade height was exhibited for the single-stage modified turbine with the nozzle having the largest total passage area (H). The blade efficiency was increased from 0.47 to 0.54 at design speed and pressure ratio by increasing the blade height from 0.35 to 0.45 inch.

6. The effect on the performance of the single-stage modified turbine of changing the blade-inlet angle from 17° to 20° was found to be negligible.

7. A decrease of 0.07 in blade efficiency resulted when the shrouds were removed from the 0.35-inch blades.

8. Consideration of the losses affecting turbine performance indicated that further improvement would originate only from decreasing the following losses: (a) leaving losses that could be partly recovered by either a more effective second stage or by a suitably designed stator row and diffuser; and (b) losses resulting from large turning of supersonic flow, which might be decreased by an improved blade-passage design.

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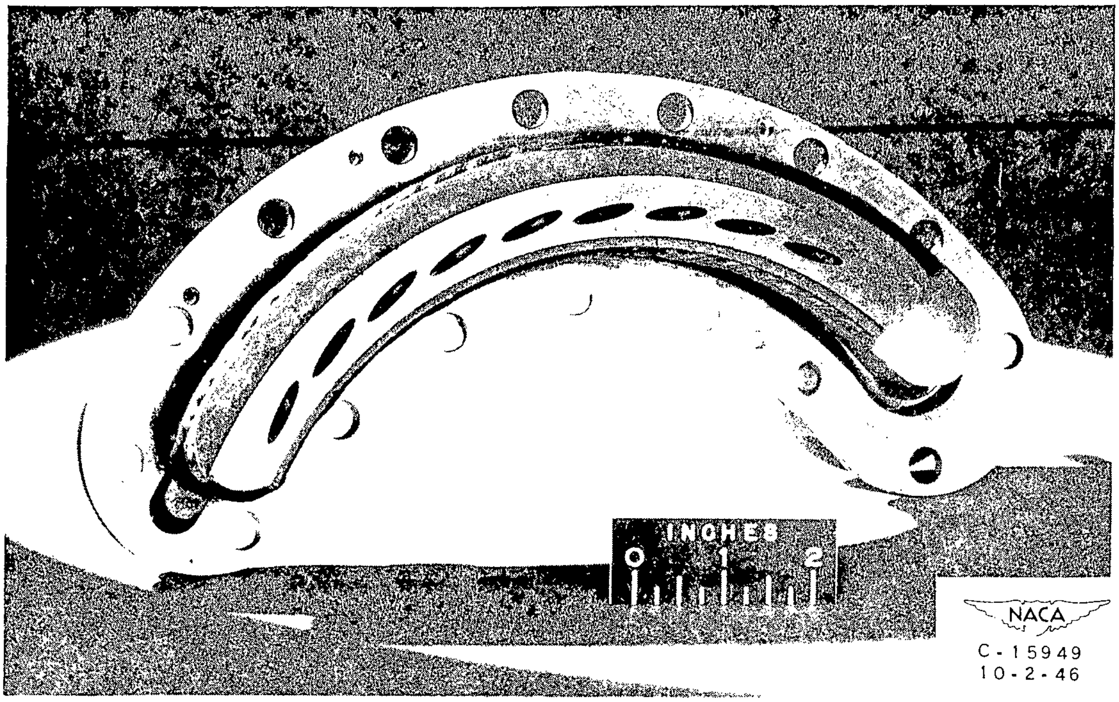
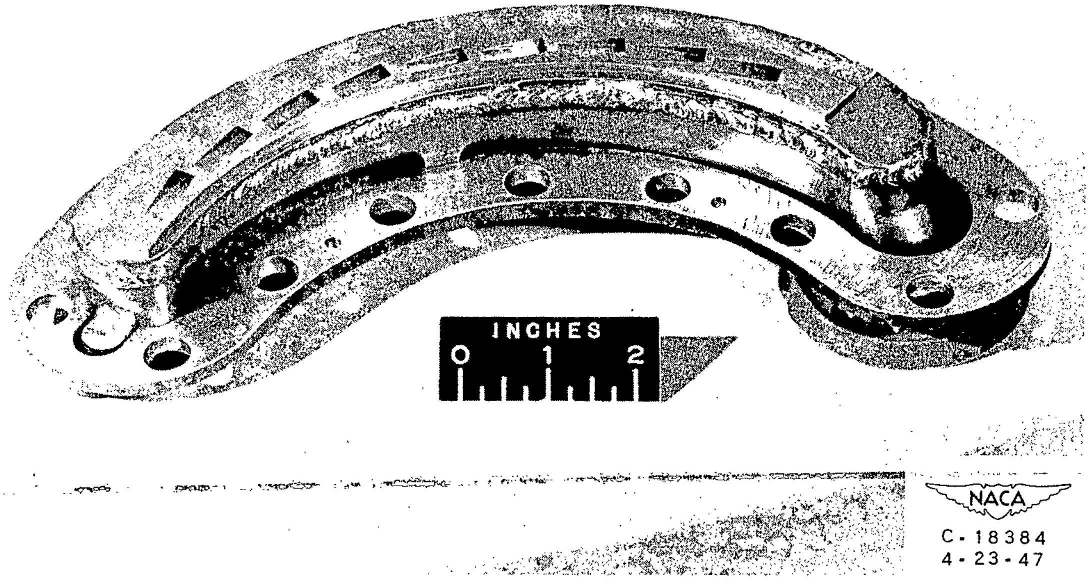


(a) Nozzle E.



(b) Nozzle H.

Figure 1. - Outlet face of various nozzles designed for turbine of Mark 25 aerial-torpedo power plant.

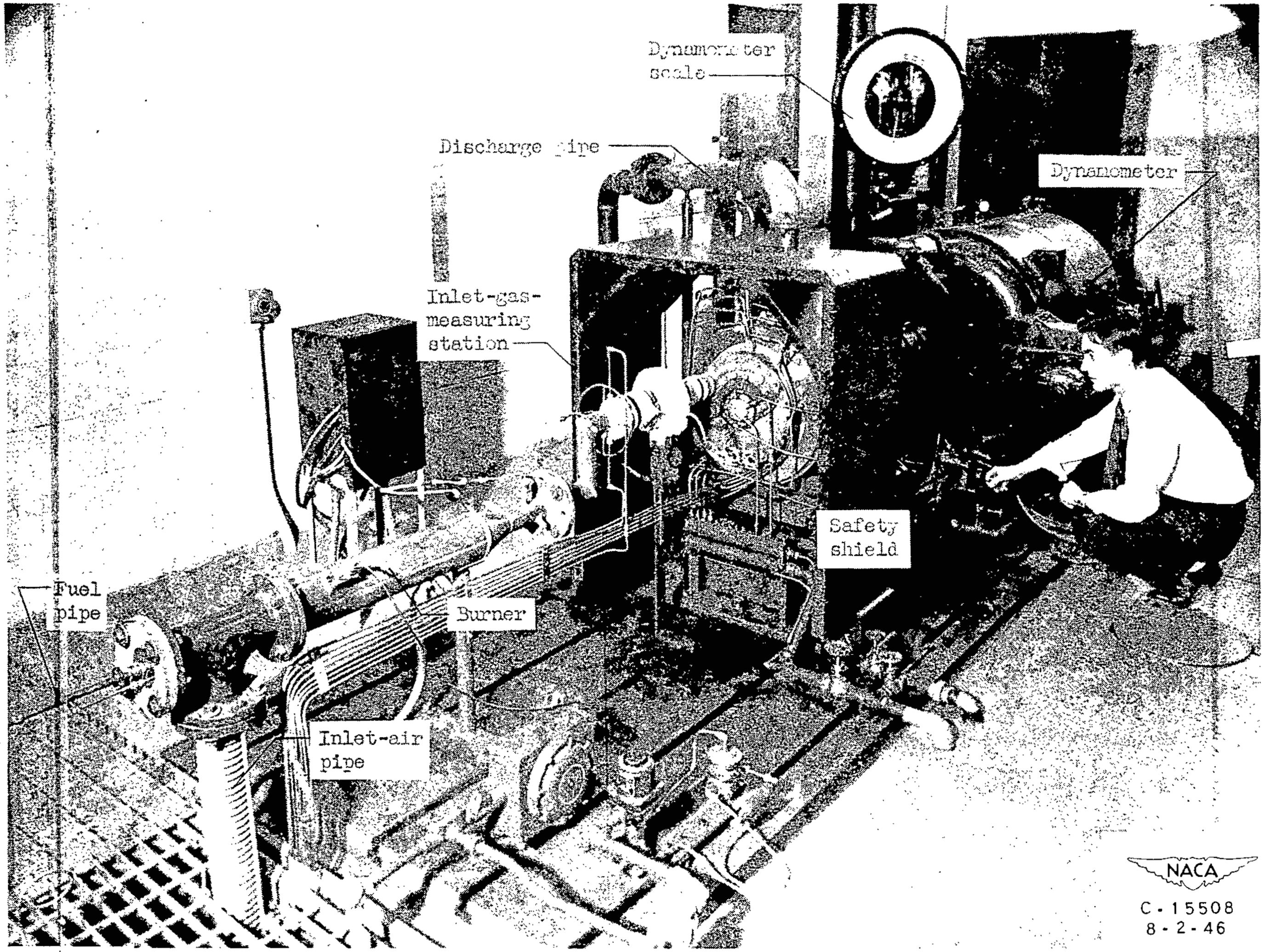


Figure 2. - Set-up for investigation of turbine of Mark 25 aerial-torpedo power plant.

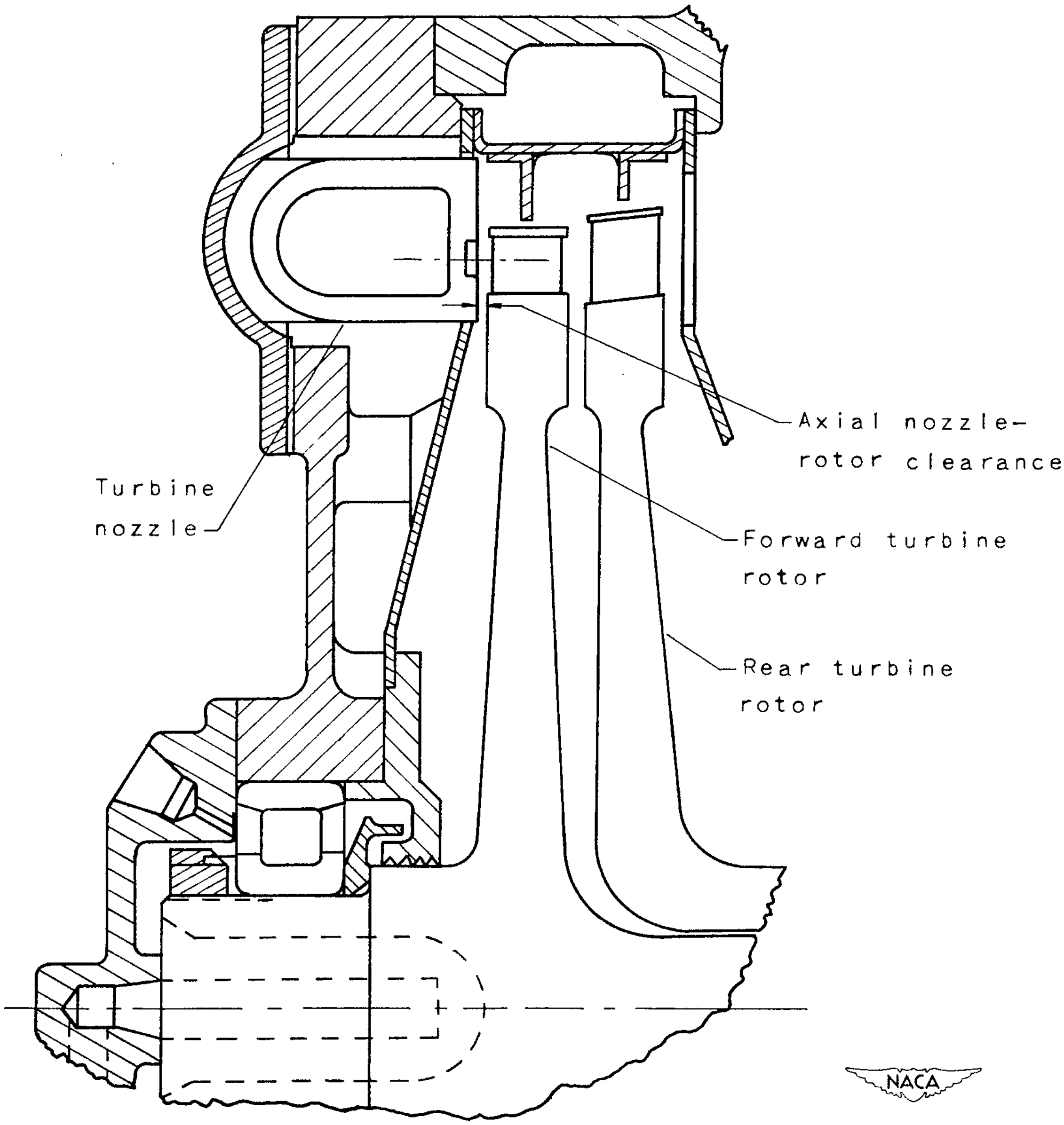
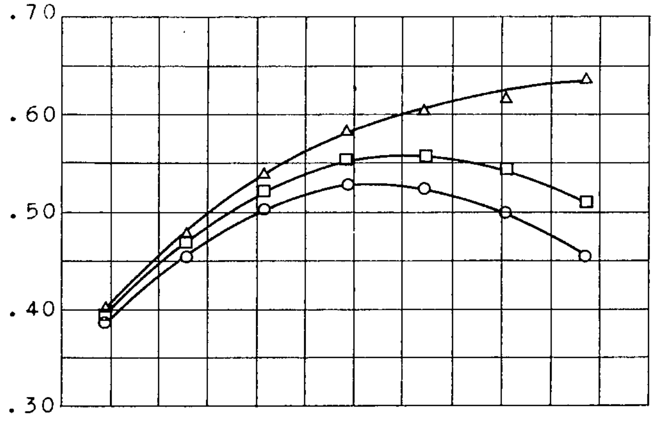
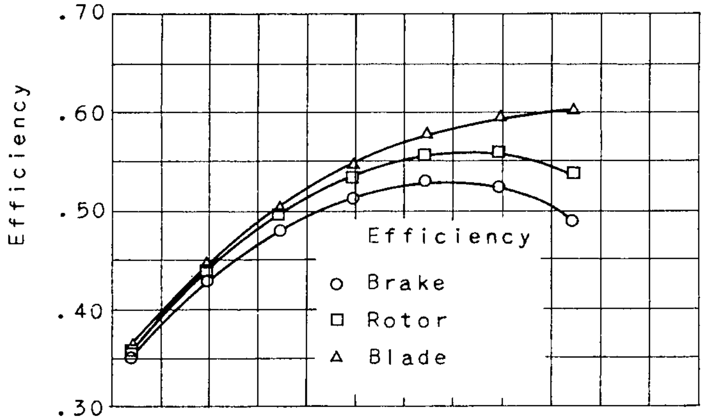


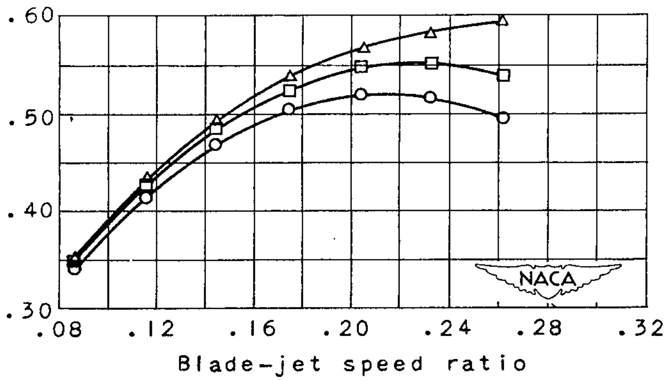
Figure 3. - Nozzle and-turbine-rotor assembly for Mark 25 aerial-torpedo power plant.



(a) Pressure ratio, 8.

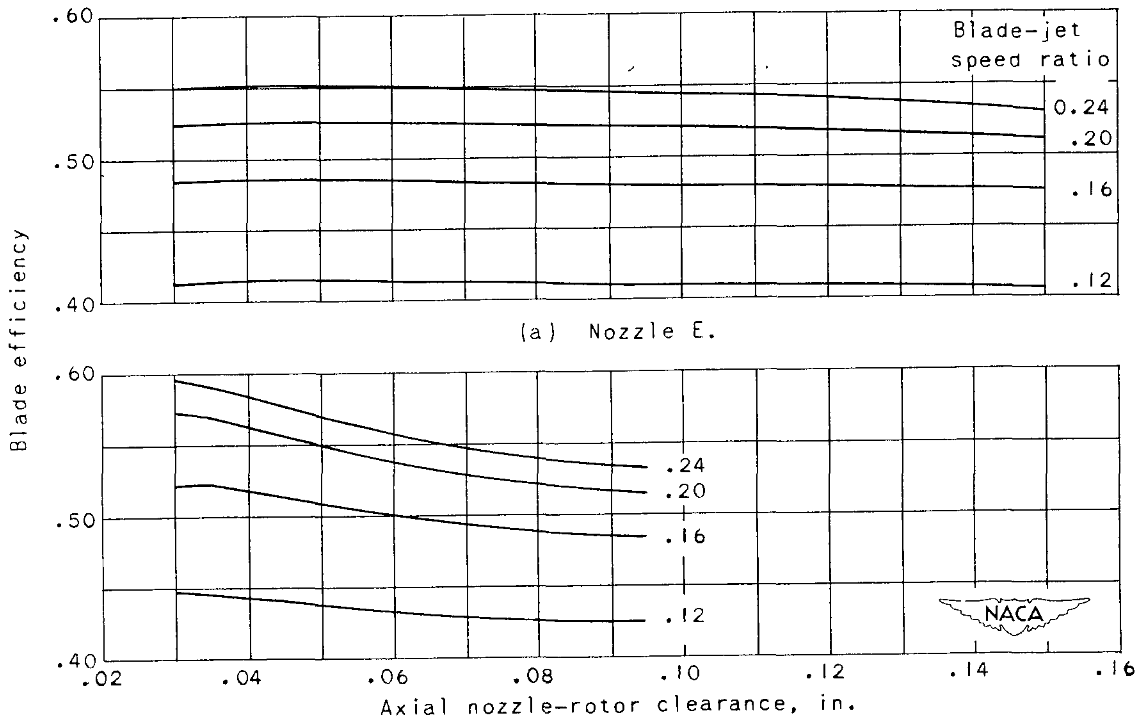


(b) Pressure ratio, 15.



(c) Pressure ratio, 19.

Figure 4. - Variation of brake, rotor, and blade efficiencies with blade-jet speed ratio for two-stage Mark 25 aerial-torpedo turbine with nozzle H.



(b) Nozzle H.

Figure 5. - Effect of axial nozzle-rotor clearance in Mark 25 two-stage aerial-torpedo turbine on blade efficiency at various blade-jet speed ratios with two nozzles. Pressure ratio, 15.

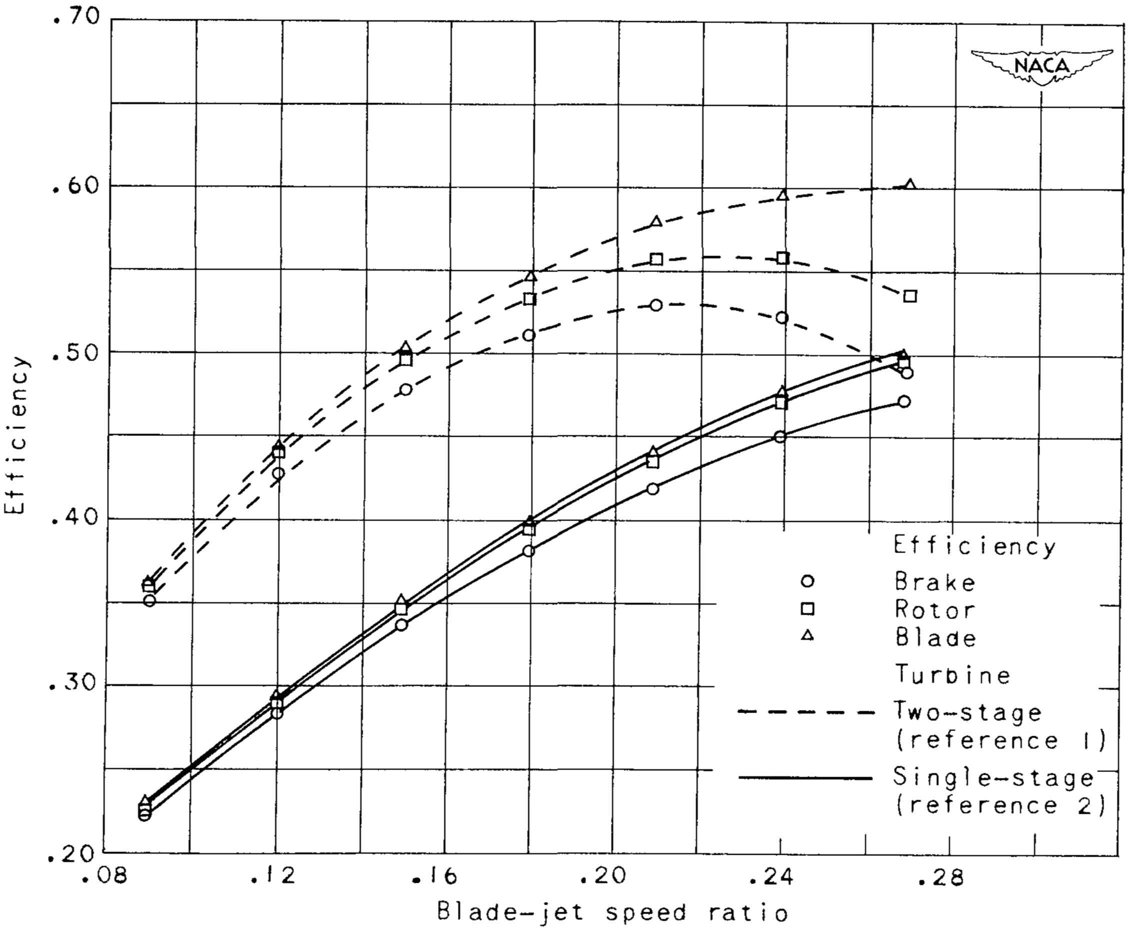
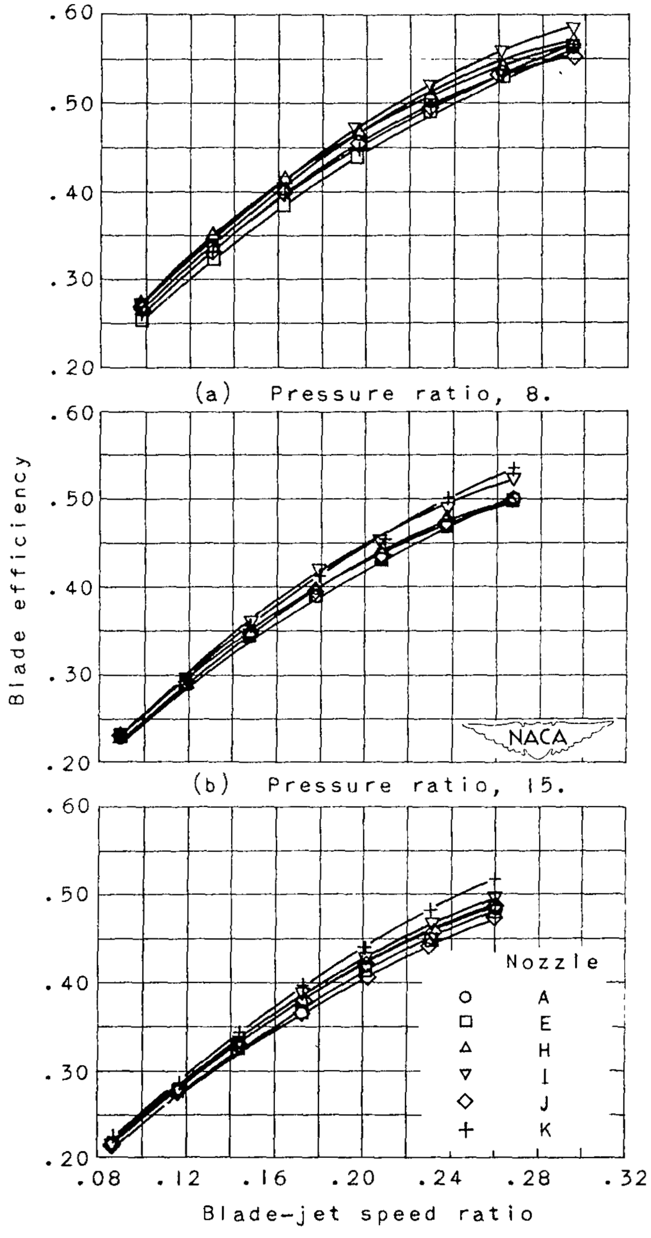


Figure 6. - Comparison of power output for single-stage modified and for standard two-stage Mark 25 aerial-torpedo turbine with nozzle H. Pressure ratio, 15.



(c) Pressure ratio, 20. Data for nozzle H were obtained at pressure ratio of 19.

Figure 7. - Variation of blade efficiency with blade-jet speed ratio for single-stage modified Mark 25 aerial-torpedo turbine with nozzles A, E, H, I, J, and K and standard rotor blades. (Data for nozzles A, E, H, and I from reference 3; data for nozzles J and K from reference 7.)

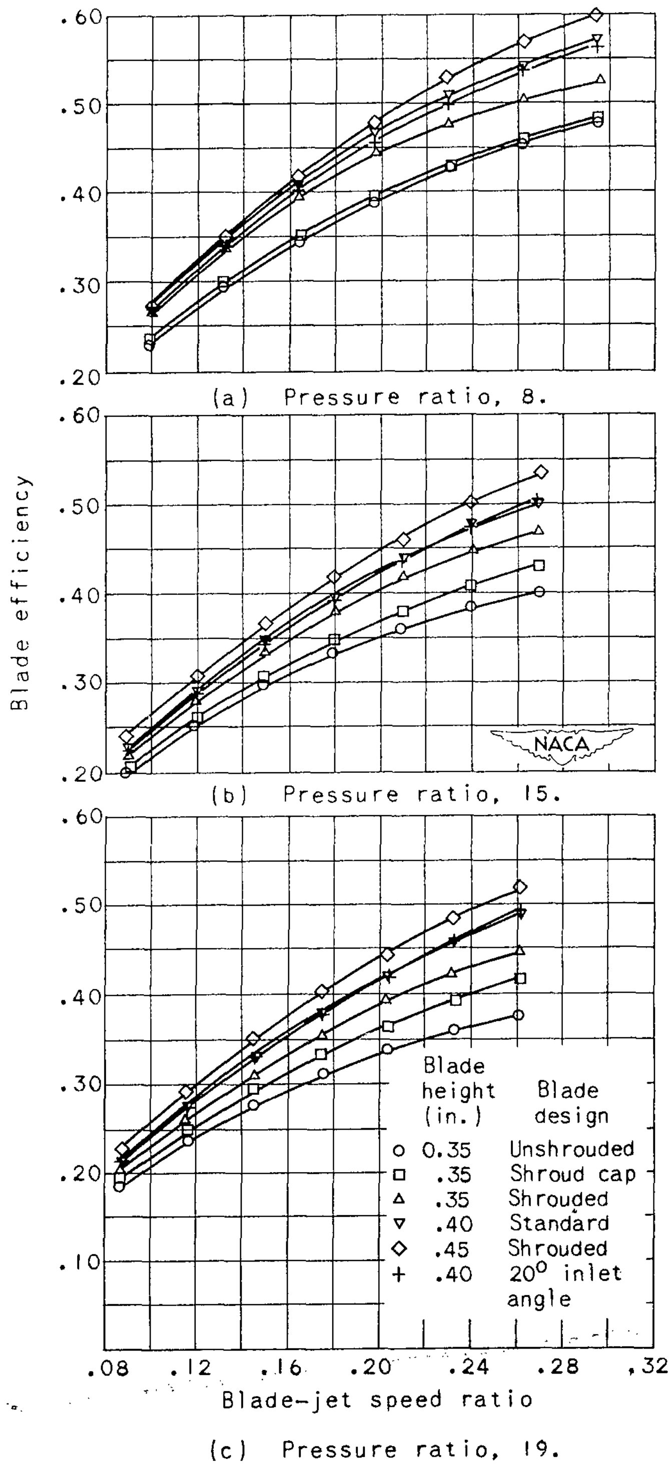


Figure 8. - Effect of blade design on performance of single-stage Mark 25 aerial-torpedo turbine with nozzle H.